(54) Title: METHOD AND APPARATUS FOR SEPARATION OF IMPULSIVE AND NON-IMPULSIVE COMPONENTS IN A SIGNAL

(57) Abstract

Impulsive components and non–impulsive components within any time–domain signal such as audio, video, vibration, etc., are separated using wavelet analysis and sorting of wavelet coefficient sets according to statistical parameters of each respective coefficient set. Each entire coefficient set is either included or excluded from each respective separated component based on the statistical parameter. Thus, automatic, adaptive, flexible, and reliable separation of impulsive and non–impulsive components is achieved.

METHOD AND APPARATUS FOR SEPARATION OF IMPULSIVE AND
NON-IMPULSIVE COMPONENTS IN A SIGNAL

The present invention relates in general to separating
5   impulsive and non-impulsive signal components within a time-
domain signal, and more specifically to using wavelet
transforms and sorting of wavelet coefficient sets to
separate impulsive components from non-impulsive components
of a time-domain signal.

10   This application is related to commonly owned, co-
pending U.S. application Serial no. (98-0929), entitled
"Method and Apparatus for Identifying Sound in a Composite
Sound Signal", which was filed concurrently herewith.

Time-domain signals or waveforms may often include
15   impulsive and non-impulsive components even though only one
of these components may be of interest. For example, in
either wireless or wired transmission of electrical or
electromagnetic signals, interfering signals and background
noise contaminate the signal as it travels through the
20   wireless or wired transmission channel. The transmitted
signal contains information, and therefore has primarily an
impulsive character. The interference and background noise
tends to be random and broadband, and therefore has
primarily a non-impulsive character. After transmission, it
25   would be desirable to separate the components so that the
additive noise can be removed.

In other applications, sound waves may be converted to
electrical signals for transmission or for the purpose of
analyzing the sound to determine conditions that created the
30   sound. If the sound is a voice intended for transmission,
the picked-up sound may include an impulsive voice component
and a non-impulsive background noise component. If the
picked-up sound is created by operation of a machine or
other environmental noise, the nature of the impulsive
35   and/or non-impulsive sound components can be analyzed to
identify specific noise sources or to diagnose or
troubleshoot fault conditions of the machine, for example.

- 2 -

Prior art attempts to reduce unwanted noise and interference most often treat a signal as though the impulsive and non-impulsive components occupy different frequency bands. Thus, lowpass, highpass, and bandpass
5 filtering have been used to try to remove an undesired component. However, significant portions of the components often share the same frequencies. Furthermore, these frequency bands of interest are not known or easily determined. Therefore, frequency filtering is unable to
10 separate the components sufficiently for many purposes. Fourier analysis and various Fourier-based frequency-domain techniques have also been used in attempts to reduce undesired noise components, but these techniques also cannot separate components which share the same frequencies.
15   More recently, wavelet analysis has been used to de-noise signals. Wavelet transforms are similar in some ways to Fourier transforms, but differ in that the signal decomposition is done using a wavelet basis function over the plurality of time-versus-frequency spans, each span
20 having a different scale. In a discrete wavelet transform, the decomposed input signal is represented by a plurality of wavelet coefficient sets, each set corresponding to a respective time-versus-frequency span. De-noising signals using wavelet analysis has been done in the prior art by
25 adjusting the wavelet coefficient sets by thresholding and shrinking the wavelet coefficients prior to recovering a time-domain signal via an inverse wavelet transform. However, this technique has not resulted in the desired signals being separated to the degree necessary for many
30 applications.
    According to the present invention there is provided a method of separating impulsive and non-impulsive signal components in a time-domain signal, comprising the steps of: decomposing said time-domain signal using a wavelet
35 transform to produce a plurality of sets of wavelet coefficients, each set of wavelet coefficients corresponding to a respective time/frequency span; determining a

respective statistical parameter for each set of wavelet
coefficients; and re-synthesising a new time-domain signal
using an inverse wavelet transform applied to selected ones
of said sets of wavelet coefficients, said selected ones
5   being selected in response to said respective statistical
parameters.

     Further, according to the presence invention there is
provided an apparatus for impulsive and non-impulsive signal
separation of an input signal, comprising: a wavelet
10   transformer decomposing said input signal into a plurality
of wavelet coefficient sets; a statistical parameter
calculator calculating a statistical parameter for each
wavelet coefficient set; a classifier identifying an
impulsive group of wavelet coefficient sets and a non-
15   impulsive group of wavelet coefficient sets in response to
said statistical parameters; and an inverse wavelet
transformer for synthesising an output signal from one of
said groups of wavelet coefficient sets.

20   The invention will now be described, by way of example,
with reference to the accompanying drawings, in which:
     Figure 1 is a functional block diagram showing a de-
noising process of the prior art;
     Figure 2 is a functional block diagram showing an
25   improved signal separation process of the present
invention;
     Figure 3 is a block diagram showing an implementation
of the present invention in greater detail;
     Figure 4 is a flowchart showing a preferred method of
30   the present invention; and
     · Figure 5 is a schematic block diagram showing
customized hardware for implementing the present
invention.

35   Wavelet analysis has been used in the past to remove
noise from data using a technique called wavelet shrinkage
and thresholding. A wavelet transform decomposes a signal

into wavelet coefficients, some of which correspond to fine
details of the input signal and others of which correspond
to gross approximations of the input signal. Wavelet
shrinkage and thresholding resets all coefficients to zero
5   which have a value less than a threshold. This reduces the
fine details which is where certain noise components may be
represented. Thereafter, the modified coefficients are
applied to an inverse transform to reproduce the input
signal with some fine details missing, and therefore with a
10   reduced noise level. As shown in Figure 1, a time-domain
signal is applied to a discrete wavelet transform (DWT) 10.
As a result of the decomposition, a plurality of wavelet
coefficient sets 11, individually designated as CS1 through
CS8, are produced. Each coefficient set corresponds to a
15   respective time-versus-frequency span and has a plurality of
datapoint samples. The number and locations of the time-
versus-frequency spans are selected to maximize performance
in any particular application. Typically, the range between
an upper and a lower frequency is divided geometrically
20   (e.g., logarithmically) into the desired number of time-
versus-frequency spans. The plurality of coefficient sets
11 are each adjusted according to the thresholding criteria
of the wavelet shrinkage and thresholding technique in a
plurality of adjustment blocks 12. The adjusted coefficient
25   sets are provided to an inverse discrete wavelet transform
(IDWT) 13 which reproduces a de-noised time-domain signal.
        While the technique of Figure 1 can be effective in
reducing gaussian-type noise in a noisy data signal, the
degree of signal separation obtained in certain applications
30   (such as clearly separating impulsive and non-impulsive,
non-gaussian components) is not fully achieved. Such signal
separation is greatly improved using the present invention
as shown generally in Figure 2. A time-domain input signal
15 is input to a wavelet transform 16. A plurality of
35   resulting wavelet coefficient sets are input to a kurtosis
calculation 17. A kurtosis value β is determined for each
of the wavelet coefficient sets according to the ratio of

- 5 -

the fourth-order central moment to the squared second-order
central moment of the individual coefficient values within
each wavelet coefficient set. Each coefficient set has
about the same number of datapoints as input signal 15.
5   Each wavelet coefficient set corresponds to a different
level or scale of the wavelet transform. Rather than modify
values within each respective wavelet coefficient set as in
the prior art, the present invention sorts the wavelet
coefficient sets according to the respective kurtosis values
10   or with respect to some other statistical parameter. Based
upon this sorting of coefficient sets, the respective
impulsive and non-impulsive components of the input signal
are separated.

     Thus, the wavelet coefficient sets are sorted into
15   coefficient sets 18 having kurtosis values β greater than a
predetermined kurtosis threshold and coefficient sets 19
having kurtosis values β less than the predetermined
kurtosis threshold. Coefficient sets 18 are passed through
an inverse wavelet transform 20 to reproduce the impulsive
20   component 21. Coefficient sets 19 are passed through an
inverse wavelet transform 22 to produce the non-impulsive
component 23. Either or both of these signal components are
coupled to an output device 24 which may include an audio
transducer or a video display for reproducing audio and
25   video signals, for example.

     The kurtosis value is a preferred statistical parameter
for separating the impulsive and non-impulsive components.
However, other statistical parameters can be used such as
mean, standard deviation, skewness, and variance.
30   Furthermore, the threshold employed for separating the
signal components may take on different values depending
upon the signal sources. In general, a kurtosis threshold
equal to about 5 provides good results.

     A specific implementation of the present invention is
35   shown in greater detail in Figure 3. A time-domain signal
having impulsive and non-impulsive components which are
desired to be separated is input to a discrete wavelet

transform (DWT) 25. A conventional DWT is employed. A
selected basis function and the number of spans and
locations for each time-versus-frequency span must be
specified as is known in the art. A plurality of sets of
5   wavelet coefficients CS1 through CS4 are generated in blocks
26-29. Typically, the number of time-versus-frequency spans
is greater than four, but four are shown to simplify the
drawing. In many applications, a span number of eight has
been found to provide good performance.

10   CS1 block 26 is coupled to a kurtosis calculation block
30. The kurtosis value from kurtosis calculation block 30
is provided to a classifier/comparator 31. A predetermined
threshold is also provided to classifier/comparator 31 and
is compared with the kurtosis value. Depending upon the
15 result of the comparison, classifier/comparator 31 controls
a multiplex switch 32. The input of multiplex switch 32
receives coefficient set CS1. The switch output may be
switched to either an impulsive IDWT 36 or a non-impulsive
IDWT 37. Coefficient blocks 27-29 and multiplex switches
20 33-35 are each connected to respective identical kurtosis
calculation blocks and classifier/comparator blocks (not
shown). Thus, coefficient sets having a kurtosis value
greater than the threshold are provided through their
respective multiplex switches to the impulsive IDWT, thereby
25 producing a time-domain impulsive signal. Coefficient sets
having a kurtosis value less than the threshold are switched
to non-impulsive IDWT 37 to produce a time-domain non-
impulsive signal.

         A preferred embodiment of a method according to the
30 present invention is shown in Figure 4. In step 40, a basis
function, the number and location of time-versus-frequency
spans, and a predetermined threshold are selected for a
particular application of impulsive and non-impulsive signal
separation. One example of an appropriate basis function
35 may be the Debauchies 40 basis function. A preferred number
of time-versus-frequency spans is about eight, with the
spans covering frequencies from zero to 22 kHz (using a

- 7 -

common sampling rate of 44 kHz for audio signals). The
spans are arranged geometrically and do not cover equal
frequency ranges. For example, a first span may cover from
11 kHz to 22 kHz. A second span covers from 5.5 kHz to 11

5   kHz, and so on. A preferred value for a kurtosis threshold
may be equal to about five.

        In step 41, the input signal data is decomposed into
the wavelet coefficient sets. A statistical parameter is
calculated in step 42 for each respective wavelet

10   coefficient set. In a preferred embodiment, the standard
mathematical function of calculating a kurtosis value is
employed using the individual coefficient values within a
wavelet coefficient sets as inputs to the calculation. The
output of the calculation is a single kurtosis value for the

15   coefficient set. In step 43, wavelet coefficient sets are
selected or sorted based on their respective values of the
statistical parameter. The preferred embodiment is
comprised of selecting the ones of the sets of wavelet
coefficients which all have a kurtosis value either greater

20   than or less than the kurtosis threshold, depending upon
whether the impulsive or non-impulsive component is desired
for reconstruction. In step 44, that component, or both,
are re-synthesized from the selected coefficient sets by
applying the selected coefficient sets to an inverse wavelet

25   transform. In other words, all the wavelet coefficients
within wavelet coefficient sets not to be included in a
particular inverse transform are set to zero.

        After re-synthesis, signal artifacts may have been
introduced since the inverse wavelet transform is processed

30   with truncated (i.e., set to zero) data. A typical artifact
is an erroneously increased output value at either end of
the time-domain signal. Thus, in step 45 artifacts are
removed by throwing away the endpoint samples in the re-
synthesized time-domain signal.

35   The present invention may preferably be implemented
using digital signal processing (DSP) programmable general
purpose processors or specially designed application

specific integrated circuits (ASICs), for example. Figure 5
shows a functional block diagram for implementation with
either a general purpose DSP or an ASIC. An input signal is
provided to an analog-to-digital converter 50. The input
5 signal may be digitized at a sampling frequency f_s of about
44 kHz, for example. The digitized signals are provided to
a discrete wavelet transform (DWT) 51. After decomposition,
DWT 51 provides a plurality of wavelet coefficient sets to a
coefficient-set random access memory (CSRAM) 52. The
10 coefficient sets from CSRAM 52 are provided to a bank of
transmission gates 53 comprised of AND-gates. Each
coefficient set is coupled to two transmission gates which
are inversely controlled as described below. The outputs of
each pair of transmission gates are respectively connected
15 to either IDWT 54 or IDWT 55. IDWT 54 provides the
impulsive output signal after passing the inverse transform
signal through a digital-to-analog converter 56. The output
of IDWT 55 is connected to a digital-to-analog converter 57
which provides the non-impulsive signal.
20   Various control inputs are provided to a control logic
block 60. Through these control inputs, a user can specify
various parameters for the wavelet-based signal separation
including the basis wavelet function, the number and
location of time-versus-frequency spans, the threshold
25 value, and other parameters such as the sampling rate to be
used. The transform-related parameters are provided to a
configuration block 61 which configures DWT 51 and IDWT's 54
and 55.
        Control logic 60 also provides the threshold value to a
30 threshold register 62. The threshold value is provided from
threshold register 62 to the inverting inputs of a plurality
of comparators 63-66. The non-inverting inputs of
comparators 63-66 receive kurtosis values β for respective
coefficient sets from a plurality of kurtosis calculators
35 67-70, respectively. The output of each comparator controls
a pair of transmission gates which correspond to the
coefficient set for which the comparator also receives the

respective kurtosis value. The comparator output is
inverted at the input to one transmission gate so that the
respective coefficient set is coupled to only one of the
IDWTs 54 or 55. Thus, the impulsive and non-impulsive
5   signal components are separated and are available at the
outputs of the DSP or ASIC and may be selectively used for
any desired application.

Based on the foregoing, the present invention
automatically detects and separates impulsive signal
10   components (such as static noises in communication signals
or road-induced squeaks and rattles in automobiles) from
non-impulsive components (such as background noise) for any
types of signals using a predetermined threshold. The
invention is adaptive to different types of signals and
15   threshold levels. The invention achieves fast processing
speed and may be implemented using general or customized
integrated circuits. The invention may be used to identify
and separate out impulsive noise signatures reflecting
abnormalities of machine operations (e.g., bearing failure,
20   quality control issues, etc.). The invention is also useful
in communication, medical imaging and other applications
where other impulsive noises or information need to be
separated such as in the isolation of static noises,
extraneous noises, vibrations or disturbances, and others.

CLAIMS

1. A method of separating impulsive and non-impulsive
signal components in a time-domain signal, comprising the
steps of:

decomposing said time-domain signal using a wavelet
transform to produce a plurality of sets of wavelet
coefficients, each set of wavelet coefficients
corresponding to a respective time/frequency span;

determining a respective statistical parameter for each
set of wavelet coefficients; and

re-synthesising a new time-domain signal using an
inverse wavelet transform applied to selected ones of said
sets of wavelet coefficients, said selected ones being
selected in response to said respective statistical
parameters.

2. A method as claimed in claim 1, wherein said
selected ones of said sets of wavelet coefficients are
determined by comparing each respective statistical
parameter with a predetermined threshold.

3. A method as claimed in claim 1 or 2, wherein said
statistical parameter is comprised of a kurtosis value.

4. A method as claimed in claim 3, wherein said
selected ones of said sets of wavelet coefficients are
determined by comparing each respective kurtosis value with
a predetermined kurtosis threshold.

5. A method as claimed in claim 4, wherein said
predetermined kurtosis threshold is equal to about 5.

6. A method of removing non-impulsive signal
components from a time-domain signal, comprising the steps
of:

- 11 -

decomposing said time-domain signal using a wavelet
transform to produce a plurality of sets of wavelet
coefficients, each set of wavelet coefficients
corresponding to a respective time/frequency span;

5   determining a respective statistical parameter for each
set of wavelet coefficients;

comparing each respective statistical parameter with a
predetermined threshold; and

re-synthesising a new time-domain signal using an

10   inverse wavelet transform applied to selected ones of said
sets of wavelet coefficients for which said respective
statistical parameters are greater than said predetermined
threshold.

15   7. A method of removing impulsive signal components
from a time-domain signal, comprising the steps of:
decomposing said time-domain signal using a wavelet
transform to produce a plurality of sets of wavelet
coefficients, each set of wavelet coefficients

20   corresponding to a respective time/frequency span;
determining a respective statistical parameter for each
set of wavelet coefficients;

comparing each respective statistical parameter with a
predetermined threshold; and

25   re-synthesising a new time-domain signal using an
inverse wavelet transform applied to selected ones of said
sets of wavelet coefficients for which said respective
statistical parameters are less than said predetermined
threshold.

30

8. Apparatus for impulsive and non-impulsive signal
separation of an input signal, comprising:
a wavelet transformer (25) decomposing said input
signal into a plurality of wavelet coefficient sets;

35   a statistical parameter calculator (30) calculating a
statistical parameter for each wavelet coefficient set;

- 12 -

a classifier (31) identifying an impulsive group of wavelet coefficient sets and a non-impulsive group of wavelet coefficient sets in response to said statistical parameters; and

5   an inverse wavelet transformer (36,37) for synthesising an output signal from one of said groups of wavelet coefficient sets.

9.   An apparatus as claimed in claim 8, wherein said
10 classifier identifies said impulsive group of wavelet coefficient sets as those having statistical parameters greater than a predetermined threshold and identifies said non-impulsive group of wavelet coefficient sets as those having statistical parameters less than said predetermined
15 threshold.

10. An apparatus as claimed in claim 9 wherein said statistical parameter is a kurtosis value and said predetermined threshold is a kurtosis threshold.
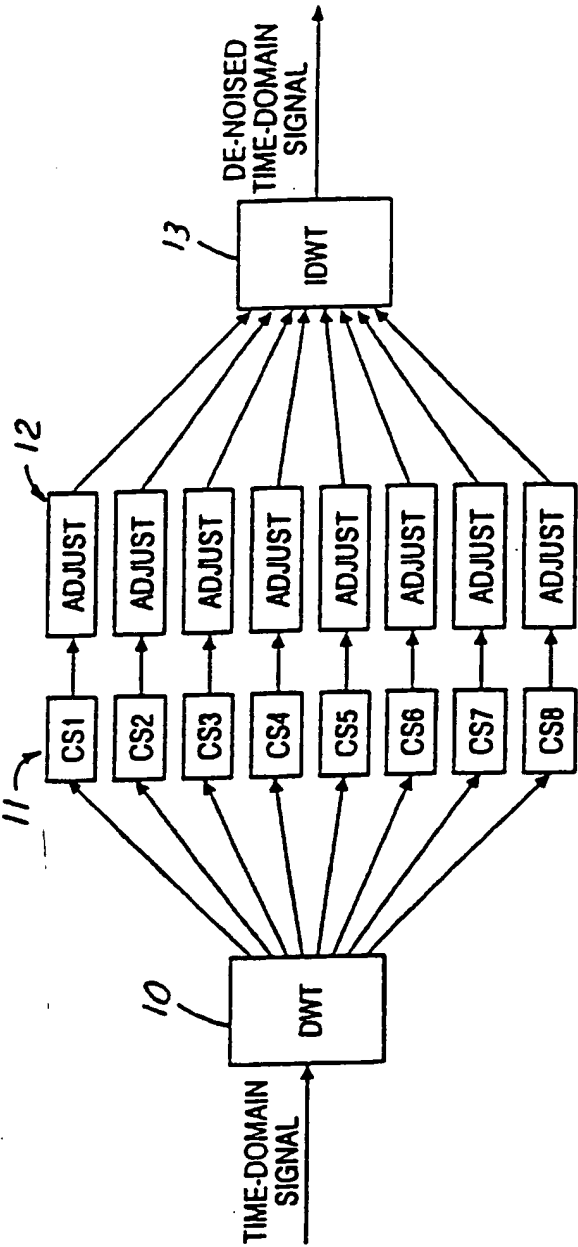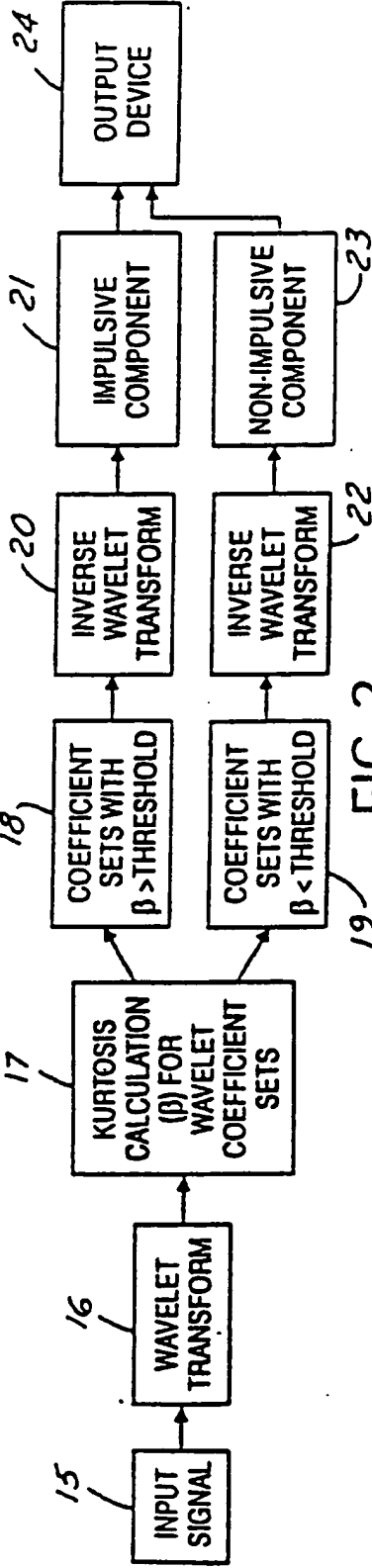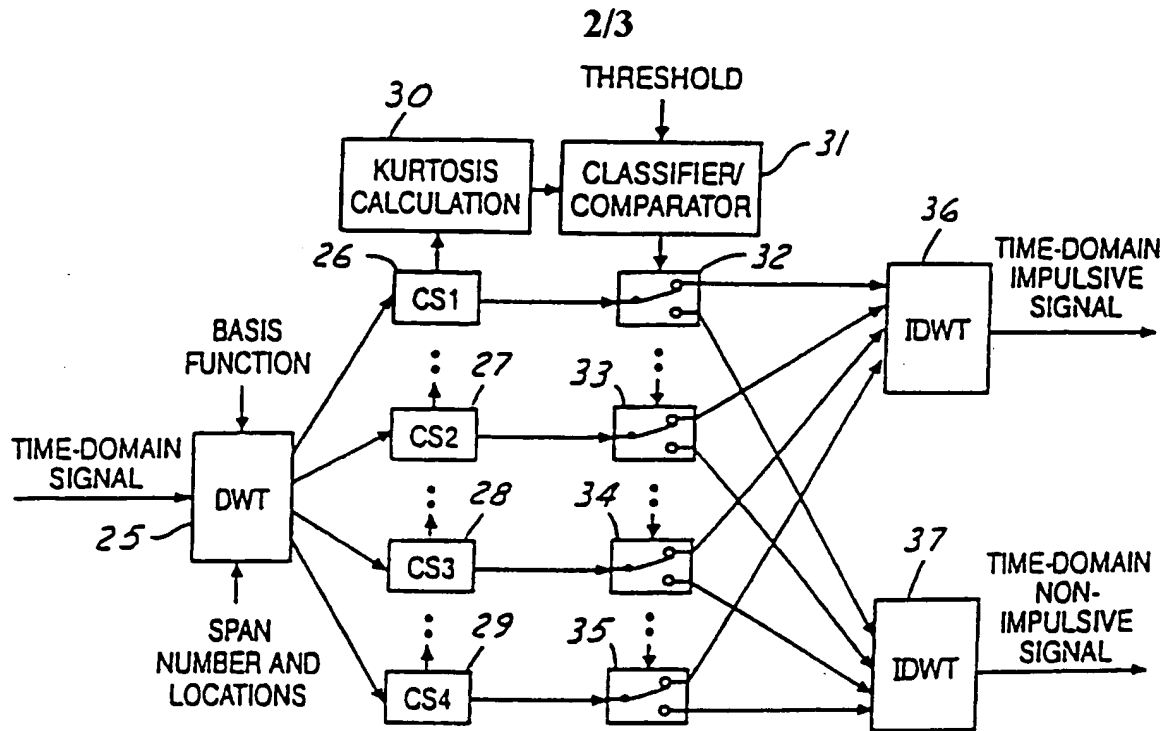20

FIG.1

(PRIOR ART)

FIG.2

THRESHOLD

KURTOSIS
CALCULATION *30*

CLASSIFIER/
COMPARATOR *31*

26 CS1 *32*

BASIS
FUNCTION

27 CS2 *33*

TIME-DOMAIN
SIGNAL

DWT

25

28 CS3 *34*

SPAN
NUMBER AND
LOCATIONS

29 CS4 *35*

IDWT *36* TIME-DOMAIN
IMPULSIVE
SIGNAL

IDWT *37* TIME-DOMAIN
NON-
IMPULSIVE
SIGNAL

FIG.3

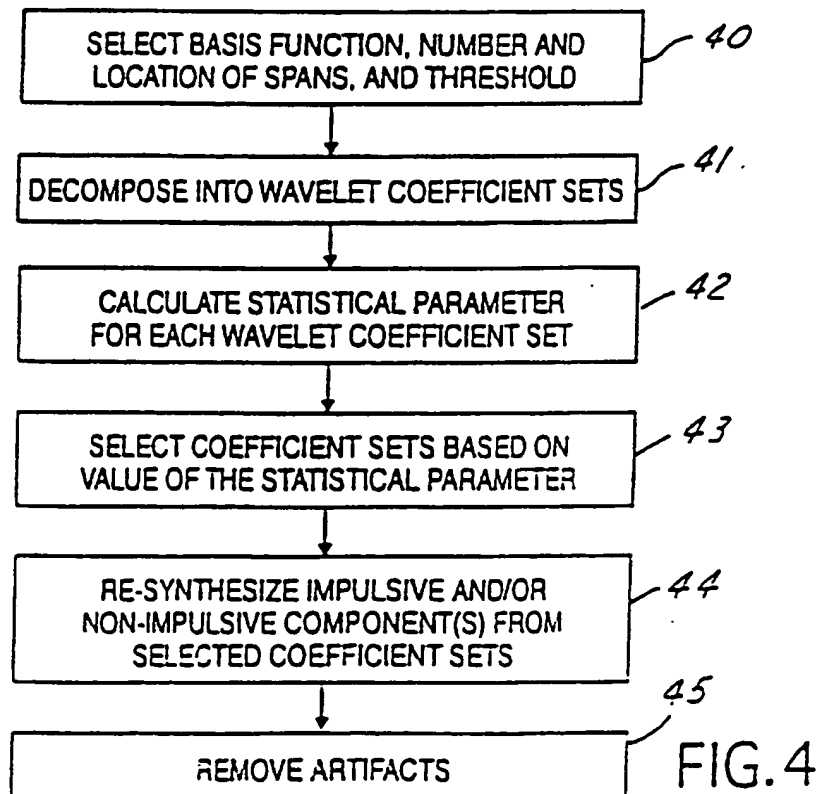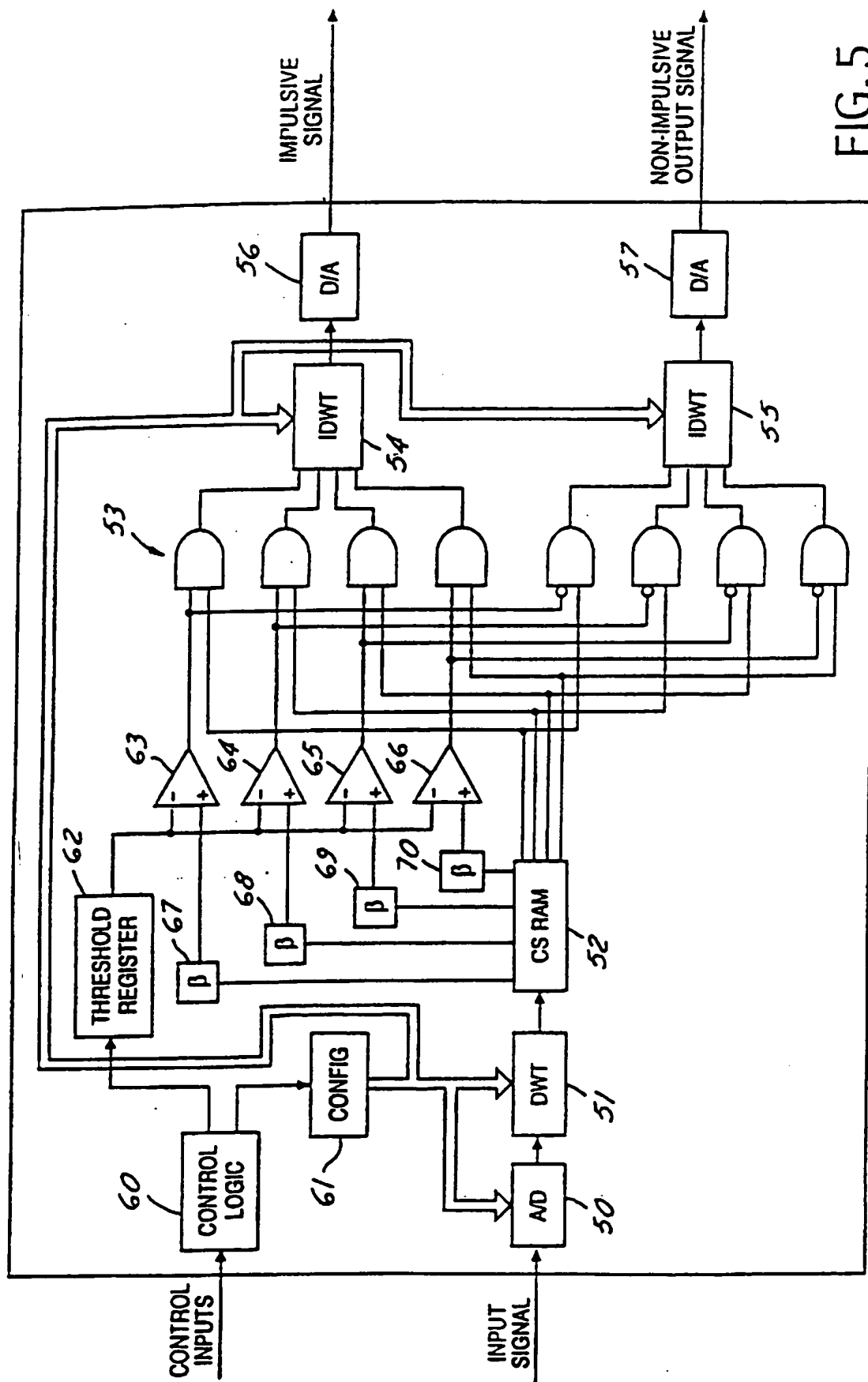|	
SELECT BASIS FUNCTION, NUMBER AND LOCATION OF SPANS, AND THRESHOLD	*40*
DECOMPOSE INTO WAVELET COEFFICIENT SETS	*41*
CALCULATE STATISTICAL PARAMETER FOR EACH WAVELET COEFFICIENT SET	*42*
SELECT COEFFICIENT SETS BASED ON VALUE OF THE STATISTICAL PARAMETER	*43*
RE-SYNTHESIZE IMPULSIVE AND/OR NON-IMPULSIVE COMPONENT(S) FROM SELECTED COEFFICIENT SETS	*44*
REMOVE ARTIFACTS	*45*

FIG.4

FIG.5

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G10L21/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G10L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DATABASE INSPEC 'Online! INSTITUTE OF ELECTRICAL ENGINEERS, STEVENAGE, GB RAVIER P ET AL: "Denoising using wavelet packets and the kurtosis: application to transient detection" Database accession no. 6232160 XP002122333 abstract & PROCEEDINGS OF THE IEEE-SP INTERNATIONAL SYMPOSIUM ON TIME-FREQUENCY AND TIME-SCALE ANALYSIS (CAT. NO.98TH8380), PROCEEDINGS OF INTERNATIONAL SYMPOSIUM ON TIME-FREQUENCY AND TIME-SCALE ANALYSIS, PITTSBURGH, PA, USA, 6-9 OCT. 1998, pages 625-628, 1998, New York, NY, USA, IEEE, USA ISBN: 0-7803-5073-1 page 625, right-hand column, line 1 - line -/--	1-3,6-10

[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure. use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 November 1999	26/11/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office. P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040. Tx. 31 651 epo nl. Fax: (+31-70) 340-3016	Van Doremalen, J

	C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT	
Category	Citation of document, with indication,where appropriate. of the relevant passages	Relevant to claim No.
	22 page 626, left-hand column, line 1 - line 25 ---	
A	WONG R S C ET AL: "DENOISING OF LOOW SNR SIGNALS USING COMPOSITE WAVELET SHRINKAGE" IEEE PACIFIC RIM CONFERENCE ON COMMUNICATIONS, COMPUTERS AND SIGNAL PROCESSING,US,NEW YORK, NY: IEEE, vol. CONF. 6, page 302-305 XP000804652 ISBN: 0-7803-3906-1 abstract page 302, right-hand column, line 13 - line 25 page 303, left-hand column, line 1 - line 21 ---	1,6-8
A	RAVIER P ET AL: "Combining an adapted wavelet analysis with fourth-order statistics for transient detection" SIGNAL PROCESSING. EUROPEAN JOURNAL DEVOTED TO THE METHODS AND APPLICATIONS OF SIGNAL PROCESSING,NL,ELSEVIER SCIENCE PUBLISHERS B.V. AMSTERDAM, vol. 70, no. 2, page 115-128 XP004143557 ISSN: 0165-1684 abstract paragraphs '03.1!-'03.2! -----	1,6-8